CTP-TAMU-69/93

October 1993

$b \to s\gamma$ and ϵ_b Constraints on Two Higgs Doublet Model

GYE T. PARK

Center for Theoretical Physics, Department of Physics, Texas A&M University

College Station, TX 77843–4242, USA

and

Astroparticle Physics Group, Houston Advanced Research Center (HARC)

The Woodlands, TX 77381, USA

Abstract

We perform a combined analysis of two stringent constraints on the 2 Higgs doublet model, one coming from the recently announced CLEO II bound on $B(b \to s\gamma)$ and the other from the recent LEP data on ϵ_b. We have included one-loop vertex corrections to $Z \to b\bar{b}$ through ϵ_b in the model. We find that the new ϵ_b constraint excludes most of the less appealing window $\tan\beta \lesssim 1$ at 90%C. L. for $m_t = 150\,\mathrm{GeV}$. We also find that although $b \to s\gamma$ constraint is stronger for $\tan\beta > 1$, ϵ_b constraint is stronger for $\tan\beta \lesssim 1$, and therefore these two are the strongest and complimentary constraints present in the charged Higgs sector of the model.

Despite the remarkable successes of the Standard Model(SM) in its complete agreement with current all experimental data, there is still no experimental information on the nature of its Higgs sector. The 2 Higgs doublet model(2HDM) is one of the mildest extensions of the SM, which has been consistent with experimental data. In the 2HDM to be considered here, the Higgs sector consists of 2 doublets, ϕ_1 and ϕ_2, coupled to the charge -1/3 and +2/3 quarks, respectively, which will ensure the absence of Flavor-Changing Yukawa couplings at the tree level [1]. The physical Higgs spectrum of the model includes two CP-even neutral Higgs(H^0, h^0), one CP-odd neutral Higgs(A^0) , and a pair of charged Higgs($H^\pm$). In addition to the masses of these Higgs, there is another free parameter in the model, which is $\tan\beta \equiv v_2/v_1$, the ratio of the vacuum expectation values of both doublets.

With a renewed interest on the flavor-changing-neutral-current (FCNC) $b \to s\gamma$ decay, spurred by the CLEO bound $B(b \to s\gamma) < 8.4 \times 10^{-4}$ at 90% C.L. [3], it was pointed out recently that the CLEO bound can be violated due to the charged Higgs contribution in the 2HDM and the Minimal Supersymmetric Standard Model(MSSM) basically if $m_{H^\pm}$ is too light, excluding large portion of the charged Higgs parameter space [4]. The recently announced CLEO II bound $B(b \to s\gamma) < 5.4 \times 10^{-4}$ at 95%[5] excludes even larger portion of the parameter space [6]. It has certainly proven that this particular decay mode can provide more stringent constraint on new physics beyond SM than any other experiments[7]. In our previous work[8], we pointed out that in addition to the constraint from $b \to s\gamma$, the recent LEP data on $R_b(\equiv \frac{\Gamma(Z\to b\bar{b})}{\Gamma(Z\to hadrons)})$ [9] provides a mild additional constraint to the 2HDM. In this work, we will show that the recent LEP data on a new observable ϵ_b provides much stronger constraint, excluding at 90% C.L. most of the parameter space $\tan\beta \lesssim 1$, which is a less appealing window simply due to the apparent mass hierarchy $m_t \gg m_b$. ϵ_b has been recently introduced by Altarelli et. al. [11, 12] , who have proposed a new scheme

analyzing precision electroweak tests where four variables, $\epsilon_{1,2,3}$ and ϵ_b are defined in a model independent way. These four variables correspond to a set of observables $\Gamma_l, \Gamma_b, A^l_{FB}$ and M_W/M_Z. The advantage of using these variables is that one need not specify m_t and m_H. Among these variables, ϵ_b is the most interesting observable for one to consider in the 2HDM although ϵ_1 can also provide an important constraint, in the MSSM[10, 11] and a class of supergravity models[7, 14], due to a significant negative shift coming from light chargino loop in the Z wave function renormalization with the chargino mass $\sim \frac{1}{2}M_Z$. In fact, Altarelli et. al. have applied the new ϵ-analysis to the MSSM, and their conclusion is that the model is in at least as good an agreement with the data as the SM[13]. Here we intend to do a similar analysis in the framework of 2HDM.

In the 2HDM, $b \to s\gamma$ decay receives contributions from penguin diagrams with $W^\pm - t$ loop and $H^\pm - t$ loop. The expression used for $B(b \to s\gamma)$ is given by [15]

$$\frac{B(b \to s\gamma)}{B(b \to ce\bar{\nu})} = \frac{6\alpha}{\pi} \frac{\left[\eta^{16/23} A_\gamma + \frac{8}{3}(\eta^{14/23} - \eta^{16/23}) A_g + C\right]^2}{I(m_c/m_b)\left[1 - \frac{2}{3\pi}\alpha_s(m_b) f(m_c/m_b)\right]}, \tag{1}$$

where $\eta = \alpha_s(M_Z)/\alpha_s(m_b)$, I is the phase-space factor $I(x) = 1 - 8x^2 + 8x^6 - x^8 - 24x^4 \ln x$, and $f(m_c/m_b) = 2.41$ the QCD correction factor for the semileptonic decay. We use the 3-loop expressions for α_s and choose Λ_{QCD} to obtain $\alpha_s(M_Z)$ consistent with the recent measurements at LEP. In our computations we have used: $\alpha_s(M_Z) = 0.118$, $B(b \to ce\bar{\nu}) = 10.7\%$, $m_b = 4.8\,\mathrm{GeV}$, and $m_c/m_b = 0.3$. The A_γ, A_g are the coefficients of the effective $bs\gamma$ and bsg penguin operators evaluated at the scale M_Z. The contributions to $A_{\gamma,g}$ from the $W^\pm - t$ loop, the $H^\pm - t$ loop are given in Ref[15]. As mentioned above, the CLEO II bound excludes a large portion of the parameter space. In Fig. 1 we present the excluded regions in $(m_{H^\pm}, \tan\beta)$-plane for $m_t = 130$, and $150\,\mathrm{GeV}$, which lie to the left of each curve (solid). We have also imposed in the figure the lower bound on $\tan\beta$ from $\frac{m_t}{600} \lesssim \tan\beta \lesssim \frac{600}{m_b}$

obtained by demanding that the theory remain perturbative[16]. We see from the figure that at large $\tan\beta$ one can obtain a lower bound on $m_{H^\pm}$ for each value of m_t. And we obtain the bounds , $m_{H^\pm} \gtrsim 186, 244\,\mathrm{GeV}$ for $m_t = 130, 150\,\mathrm{GeV}$, respectively.

Following Altarelli et. al.[11], ϵ_b is defined from Γ_b, the inclusive partial width for $Z \to b\bar{b}$,

$$\Gamma_b = 3R_{QCD}\frac{G_F M_Z^3}{6\pi\sqrt{2}}\left(1+\frac{\alpha}{12\pi}\right)\left[\beta_b\frac{(3-\beta_b^2)}{2}{g_V^b}^2 + \beta_b^3 {g_A^b}^2\right] , \tag{2}$$

with

$$R_{QCD} \cong \left[1 + 1.2\frac{\alpha_S\,(M_Z)}{\pi} - 1.1\left(\frac{\alpha_S\,(M_Z)}{\pi}\right)^2 - 12.8\left(\frac{\alpha_S\,(M_Z)}{\pi}\right)^3\right] , \tag{3}$$

$$\beta_b = \sqrt{1-\frac{4m_b^2}{M_Z^2}} , \tag{4}$$

$$g_A^b = -\frac{1}{2}\left(1+\frac{\epsilon_1}{2}\right)(1+\epsilon_b) , \tag{5}$$

$$\frac{g_V^b}{g_A^b} = \frac{1-\frac{4}{3}\overline{s}_W^2+\epsilon_b}{1+\epsilon_b\ .} \tag{6}$$

where $\overline{s}_W^2$ is an effective $\sin^2\theta_W$ for on-shell Z and the explicit expression for ϵ_1 is given in Ref[10, 14]. ϵ_b is closely related to the real part of the vertex correction to $Z \to b\bar{b}$, ∇_b defined in Ref[19]. In the SM, the diagrams for ∇_b involve top quarks and $W^\pm$ bosons[17]. However, in the 2HDM there are additional diagrams involving $H^\pm$ bosons instead of $W^\pm$ bosons. These additional diagrams have been calculated in Ref[8, 18, 19, 20]. The charged Higgs contribution to ∇_b is given as [19]

$$\nabla_b^{H^\pm} = \frac{\alpha}{4\pi\sin^2\theta_W}\left[\frac{2v_L F_L + 2v_R F_R}{v_L^2+v_R^2}\right] , \tag{7}$$

where $F_{L,R} = F^{(a)}_{L,R} + F^{(b)}_{L,R} + F^{(c)}_{L,R}$ and

$$
\begin{aligned}
F^{(a)}_{L,R} &= b_1\left(M_{H^+}, m_t, m_b\right) v_{L,R} \lambda^2_{L,R} \ , \qquad (8) \\
F^{(b)}_{L,R} &= \left[\left(\frac{M_Z^2}{\mu^2} c_6\left(M_{H^+}, m_t, m_t\right) - \frac{1}{2} - c_0\left(M_{H^+}, m_t, m_t\right) \right) v^t_{R,L} \right. \\
&\qquad \left. + \frac{m_t^2}{\mu^2} c_2\left(M_{H^+}, m_t, m_t\right) v^t_{L,R} \right] \lambda^2_{L,R} \ , \qquad (9) \\
F^{(c)}_{L,R} &= c_0\left(m_t, M_{H^+}, M_{H^+}\right) \left(\frac{1}{2} - \sin^2\theta_W \right) \lambda^2_{L,R} \ , \qquad (10)
\end{aligned}
$$

where μ is the renormalization scale and

$$
\begin{aligned}
v_L &= -\frac{1}{2} + \frac{1}{3}\sin^2\theta_W \ , \quad v_R = \frac{1}{3}\sin^2\theta_W \ , \qquad (11) \\
v^t_L &= \frac{1}{2} - \frac{2}{3}\sin^2\theta_W \ , \quad v^t_R = -\frac{2}{3}\sin^2\theta_W \ , \qquad (12) \\
\lambda_L &= \frac{m_t}{\sqrt{2} M_W \tan\beta} \ , \quad \lambda_R = \frac{m_b \tan\beta}{\sqrt{2} M_W} \ . \qquad (13)
\end{aligned}
$$

The b_1 and $c_{0,2,6}$ above are the reduced Passarino-Veltman functions[19, 21]. The charged Higgs contribution to ϵ_b, which is negative, grows as $m_t^2/\tan^2\beta$ for $\tan\beta \ll \frac{m_t}{m_b}$ as is seen from Eq. (13). In our calculation, we neglect the neutral Higgs contributions to ∇_b which are all proportional to $m_b^2\tan^2\beta$ and become sizable only for $\tan\beta > \frac{m_t}{m_b}$ and very light neutral Higgs $\lesssim 50\,\mathrm{GeV}$, but decreases rapidly to get negligibly small as the Higgs masses become $\gtrsim 100\,\mathrm{GeV}$[20]. We also neglect oblique corrections from the Higgs bosons just to avoid introducing more paramters. However, this correction can become sizable when there are large mass splittings between the charged and neutral Higgs, for example, it can grow as $m^2_{H^\pm}$ if $m_{H^\pm} \gg m_{H^0,h^0,A^0}$. Although $\tan\beta \gg 1$ seems more appealing because of apparent hierarchy $m_t \gg m_b$, there are still no convincing arguments against $\tan\beta < 1$. Our goal

here is to see if one can put a severe constraint in this region. In Fig. 1 we also show the contours (dotted) of a predicted value of $\epsilon_b = -0.00592$, which is the LEP lower limit at 90%C. L.[11, 12]. The excluded regions lie below each dotted curve for given m_t. We do not consider higher values of m_t here because the SM prediction for ϵ_b exceeds the LEP value already for $m_t \gtrsim 163\,\text{GeV}$ [11]. For $m_t = 150(130)\,\text{GeV}$, $\tan\beta \lesssim 1.03(0.51)$ is ruled out at 90%C. L. for $m_{H^\pm} \lesssim 400\,\text{GeV}$, and $\tan\beta \lesssim 0.69(0.34)$ for $m_{H^\pm} \lesssim 800\,\text{GeV}$. We note that these strong constraints for $\tan\beta \lesssim 1$ stem from large deviations of ϵ_b from the SM prediction, which grows as $m_t^2/\tan^2\beta$ as explained above. We have also considered other constraints from low-energy data primarily in $B-\overline{B}, D-\overline{D}, K-\overline{K}$ mixing that exclude low values of $\tan\beta$[16, 22]. But it turns out that none of them can hardly compete with the present ϵ_b constraint[23]. Nevertheless, the CLEO II bound is still by far the strongest constraint present in the charged Higgs sector of the model for $\tan\beta > 1$. Therefore, we find that $b \to s\gamma$ and ϵ_b serve as the presently strongest and complimentary constraints in 2HDM.

In conclusion, we have performed a combined analysis of two stringent constraints on the 2 Higgs doublet model, one coming from the recently announced CLEO II bound on $B(b \to s\gamma)$ and the other from the recent LEP data on ϵ_b. We have included one-loop vertex corrections to $Z \to b\bar{b}$ through ϵ_b in the model. We find that the new ϵ_b constraint excludes most of the less appealing window $\tan\beta \lesssim 1$ at 90%C. L for $m_t = 150\,\text{GeV}$. We also find that although $b \to s\gamma$ constraint is stronger for $\tan\beta > 1$, ϵ_b constraint is stronger for $\tan\beta \lesssim 1$, and therefore these two are the strongest and complimentary constraints present in the charged Higgs sector of the model.

ACKNOWLEDGEMENTS

The author thanks Professor T. K. Kuo for very helpful suggestions and reading the

manuscript. This work has been supported by the World Laboratory.

References

[1] S. Glashow and S. Weinberg, Phys. Rev. D **15** (1977) 1958.

[2] S. Bertolini, F. Borzumati, A. Masiero, and G. Ridolfi, Nucl. Phys. B **353** (1991) 591.

[3] M. Battle *et al.* (CLEO Collab.) in Proceedings of the joint Lepton-Photon and Europhysics Conference on High-Energy Physics, Geneva 1991.

[4] J. Hewett, Phys. Rev. Lett. **70** (1993) 1045; V. Barger, M. Berger, and R. J. N. Phillips, Phys. Rev. Lett. **70** (1993) 1368.

[5] E. Thorndike, talk given at the 1993 Meeting of the American Physical Society, Washington D. C., April 1993; R. Ammar *et al.* (CLEO Collab.), Phys. Rev. Lett. **71** (1993) 674.

[6] V. Barger and R. J. N. Phillips, to appear in the Proceedings of the HARC workshop "Recent Advances in the Superworld", The Woodlands, Texas, April 1993.

[7] J. L. Lopez, D. V. Nanopoulos, and G. T. Park, Phys. Rev. D **48** (1993) R974; G. T. Park, to appear in the Proceedings of the HARC workshop "Recent Advances in the Superworld", The Woodlands, Texas, April 1993; J. L. Lopez, D. V. Nanopoulos, G. T. Park, and A. Zichichi, Texas A & M University preprint CTP-TAMU-40/93 (to appear in Phys. Rev. D).

[8] G. T. Park, Texas A & M University preprint CTP-TAMU-54/93 (September 1993).

[9] W. Venus, A talk given at the Lepton-Photon Conference, Cornell University, Ithaca, New York, August 1993.

[10] R. Barbieri, M. Frigeni, and F. Caravaglios, Phys. Lett. B **279** (1992) 169.

[11] G. Altarelli, R. Barbieri, and F. Caravaglios, Nucl. Phys. B **405** (1993) 3.

[12] G. Altarelli, CERN-TH.6867/93 (April 1993).

[13] G. Altarelli, R. Barbieri, and F. Caravaglios, Phys. Lett. B **314** (1993) 357.

[14] J. L. Lopez, D. V. Nanopoulos, G. T. Park, H. Pois, and K. Yuan, Phys. Rev. D **48** (1993) 3297.

[15] R. Barbieri and G. Giudice, Phys. Lett. B **309** (1993) 86.

[16] V. Barger, J. Hewett, and R. J. N. Phillips, Phys. Rev. D **41** (1990) 3421.

[17] J. Bernabeu, A. Pich, and A. Santamaria, Phys. Lett. B **200** (1988) 569; W. Beenaker and W. Hollik, Z. Phys. C40, 141(1988); A. Akhundov, D. Bardin, and T. Riemann, Nucl. Phys. B **276** (1986) 1; F. Boudjema, A. Djouadi, and C. Verzegnassi, Phys. Lett. B **238** (1990) 423.

[18] A. Djouadi, G. Girardi, C. Verzegnassi, W. Hollik, and F. Renard, Nucl. Phys. B **349** (1991) 48.

[19] M. Boulware and D. Finnell, Phys. Rev. D **44** (1991) 2054.

[20] A. Denner, R. Guth, W. Hollik, and J. Kühn, Z. Phys. C51, 695(1991).

[21] C. Ahn, B. Lynn, M. Peskin, and S. Selipsky, Nucl. Phys. B **309** (1988) 221.

[22] A. Buras et al., Nucl. Phys. B **337** (1990) 284.

[23] We have assumed that the updated analysis would not change the conclusions in Ref[16] drastically.

Figure Captions

- Figure 1: The regions in $(m_{H^\pm}, \tan\beta)$ plane excluded by the CLEO II bound $B(b \to s\gamma) < 5.4 \times 10^{-4}$ at 95%C. L., for $m_t = 130, 150\,\mathrm{GeV}$ in 2HDM. The excluded regions lie to the left of each solid curve. The excluded regions by the LEP value $\epsilon_b = -0.00592$ at 90%C. L. lie below each dotted curve. The values of m_t used are as indicated.